

# **Error Analysis in Spectral Climate Fingerprinting**

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The spectral climate fingerprinting is to use the space/time averaged spectral variation between two climate states to directly retrieve the corresponding changes in climate variables. Thus, the key process in climate fingerprinting is to attribute the spectral signal to individual climate variables.

***This attribution can be expressed as a multivariable linear regression problem:***

$$\Delta R = K \Delta X + e \quad (1a)$$

$$\Delta R_i = \sum_{j=1}^{n_x} K_{ij} \Delta x_j + e_i \quad (1b)$$

$$K_{ij} = \frac{\partial R_i}{\partial x_j}; \quad i = 1, 2, \dots, n_w; j = 1, 2, \dots, n_x \quad (1c)$$

$\Delta R = [\Delta R_1, \dots, \Delta R_{n_w}]$  Spectral change (reflectance difference between two climate states)

$\Delta X = [\Delta X_1, \dots, \Delta X_{n_x}]$  Change of climate variables to be retrieved

$K = [K]_{n_w \times n_x}$  Kernel matrix (fingerprints)

$e = [\Delta e_1, \dots, \Delta e_{n_w}]$  Errors or residuals that cannot be explained by fingerprints

Without the error consideration, the solution of Equation (1) is simply

$$\Delta X = (K^T K)^{-1} K^T \Delta R \quad (2a)$$

This is based on the ordinary least squares estimation (**LSE**).

A small error in **K** or in **ΔR** could produce large error in the solution. A linear fingerprinting solution (**LFS**) to account for the error can be expressed as :

$$\Delta X = (K^T E^{-1} K)^{-1} K^T E^{-1} \Delta R \quad (2b)$$

where **E** is the covariance matrix of **e** in Equation (1). This formulation is the same as the so-called optimal detection.

The linear expression above implies that **ΔR** and **ΔX** have to be small to maintain sufficient linearity.

We use model-simulated data to test the fingerprinting attribution in solar spectrum. Model input variables:

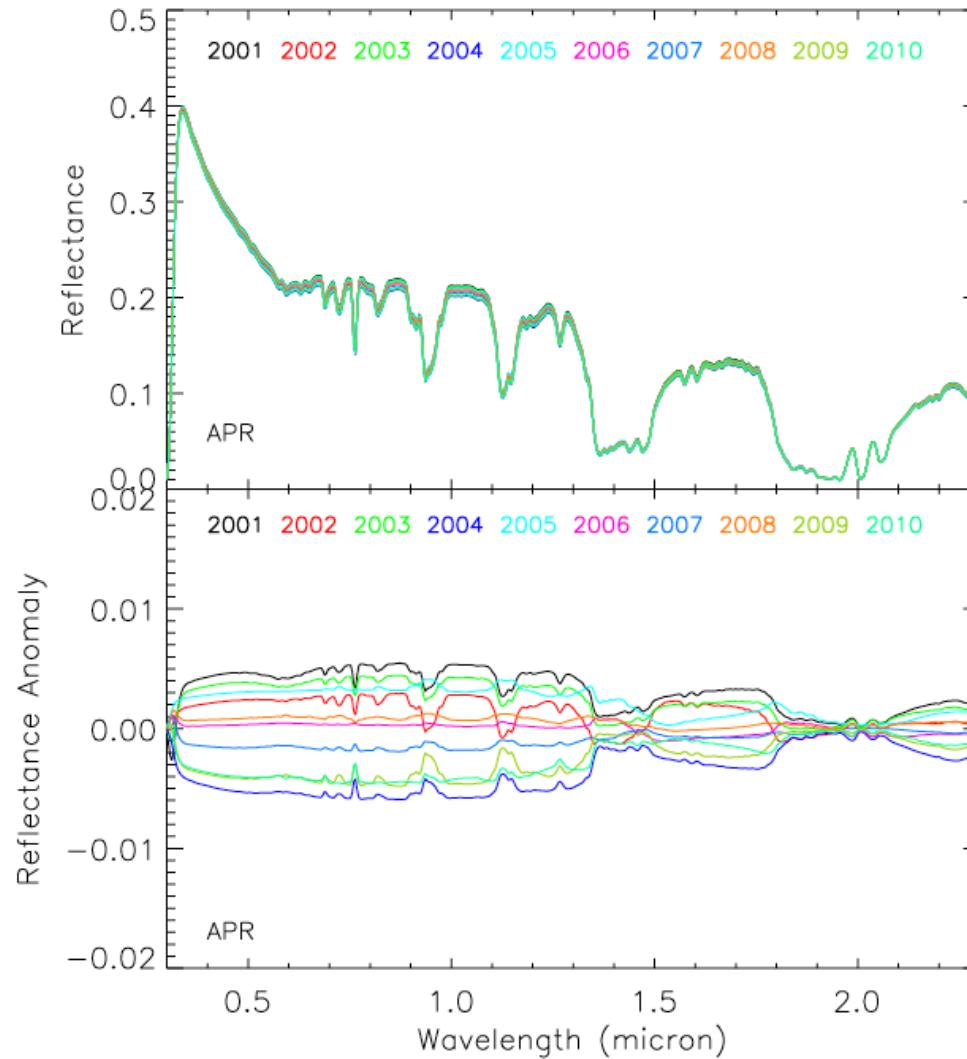
- ✓ 10 years (2001-2010) of CERES SSF data from NASA Terra satellite ;
- ✓ aerosol and cloud properties (optical depth, particle size, phase, and height) retrieved from MODIS;
- ✓ column water vapor and surface wind data from GEOS5-MERRA reanalysis;
- ✓ ozone data from SMOBA;
- ✓ ocean chlorophyll concentration from SeaWiFS.

Input these variables to the combined COART-MODTRAN model, we generate the spectral fingerprints and a time series (10 years) of monthly mean reflectance spectra (320-2300nm, 4nm resolution) to retrieve the interannual changes in the 11 relevant climate variables:

*PW, AOD, O<sub>3</sub> ..*

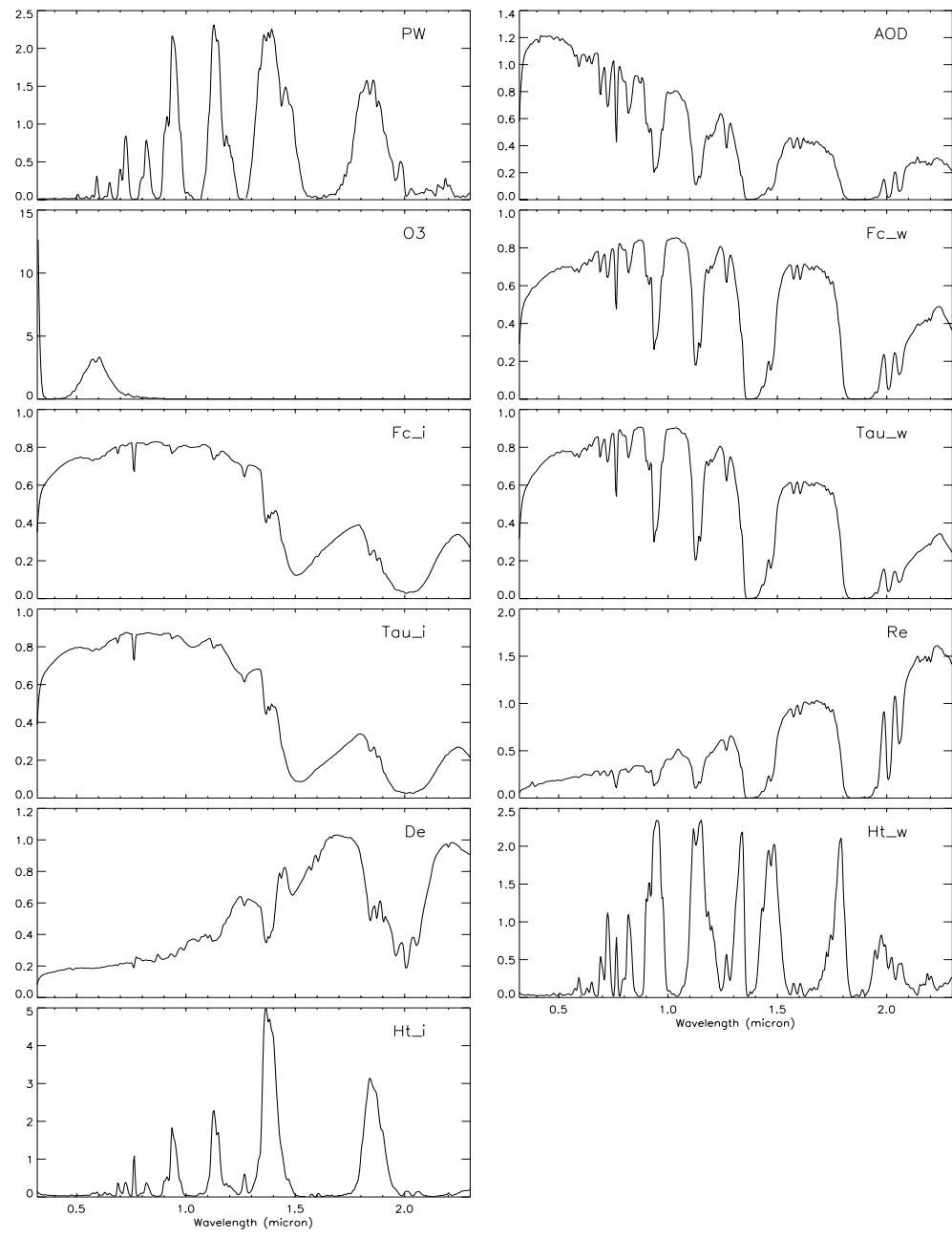
*and*

*τ, Fc, Ht, Re for water and ice clouds, respectively.*



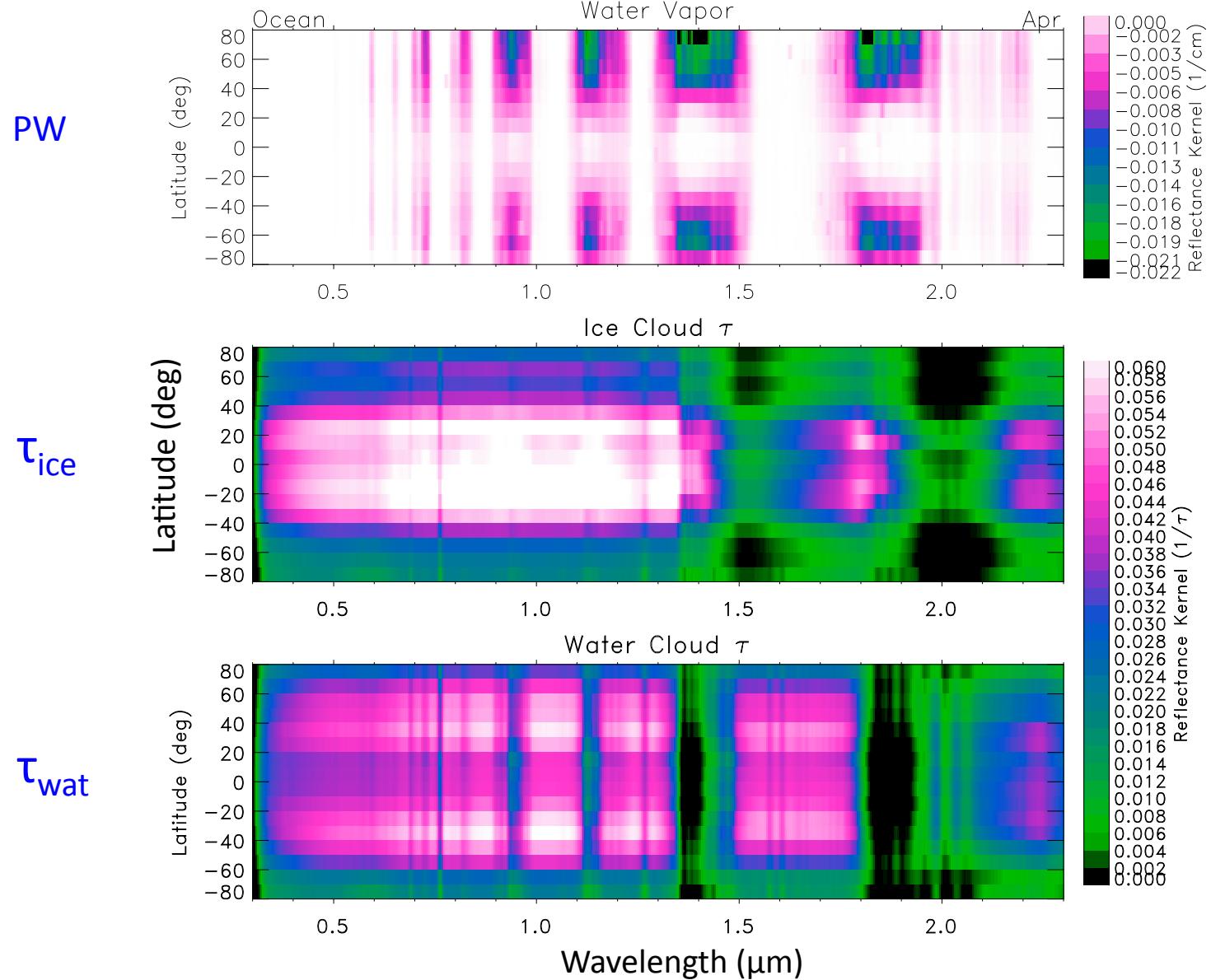
An example of the model-simulated monthly and global mean reflectance and their anomalies ( $\Delta R$ ). In each panel, each color is for a different year.

$\Delta R$  is indeed small: typically less than  $\pm 3\%$  of the mean reflectance

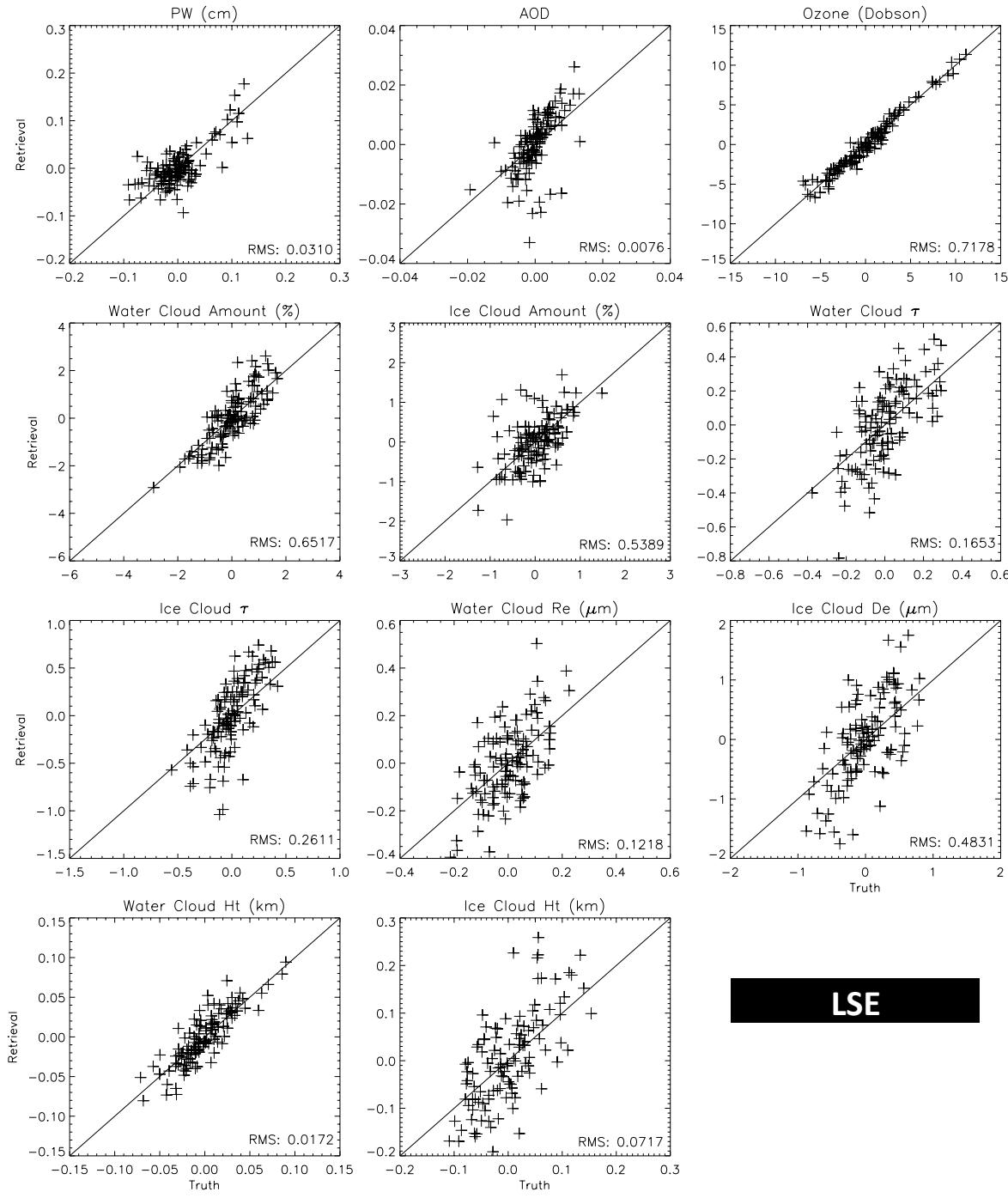


An example of global mean spectral fingerprints for the 11 variables.

(Each panel represents a different climate variable)



**An example of the zonal mean spectral fingerprints for three variables.**

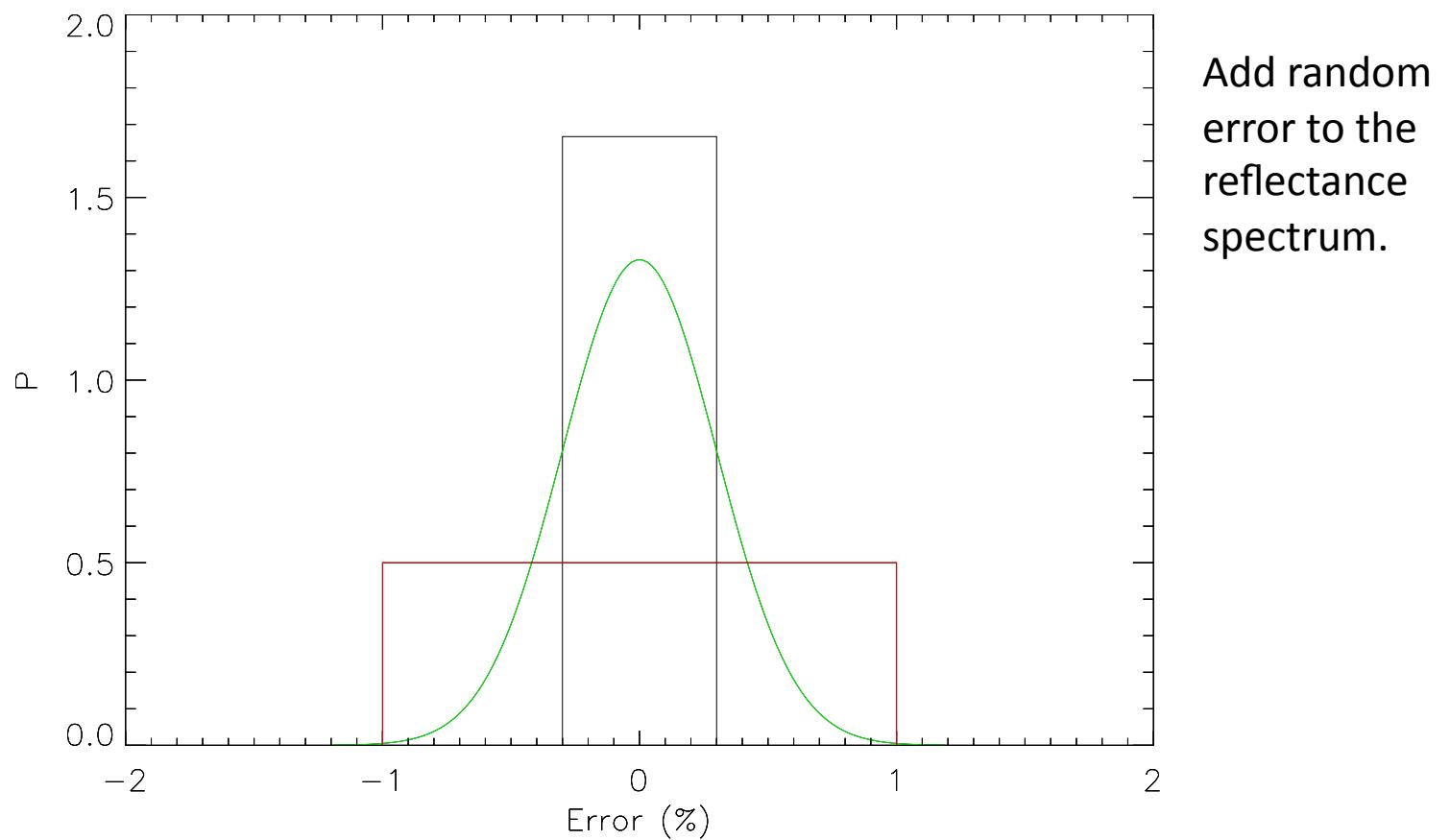


Comparison between the fingerprinting retrieval (LSE) and the model truth for the 11 variables (monthly global mean anomaly).

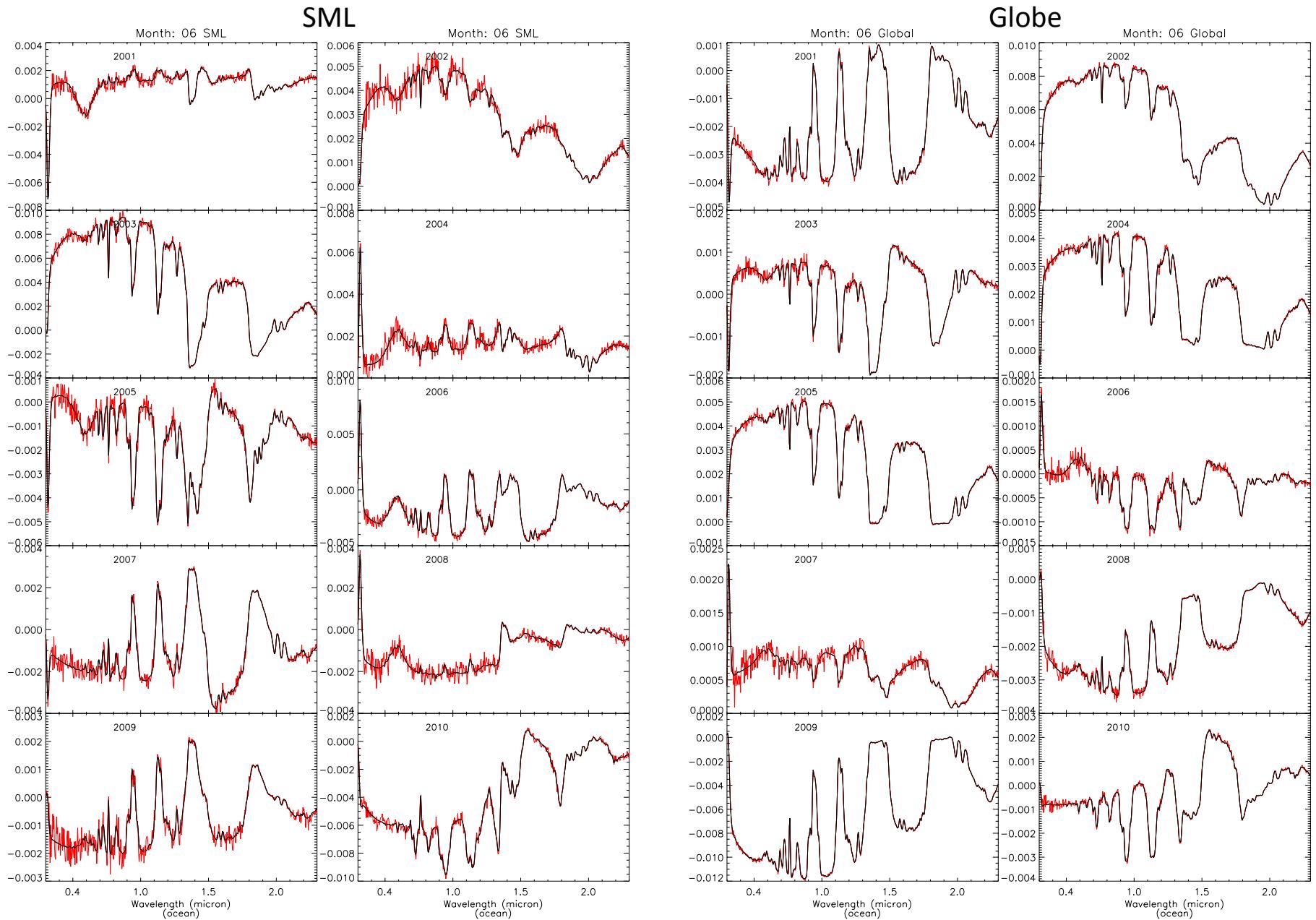
Each panel is for a different climate variable (11 total).

Error-free reflectance spectral data.

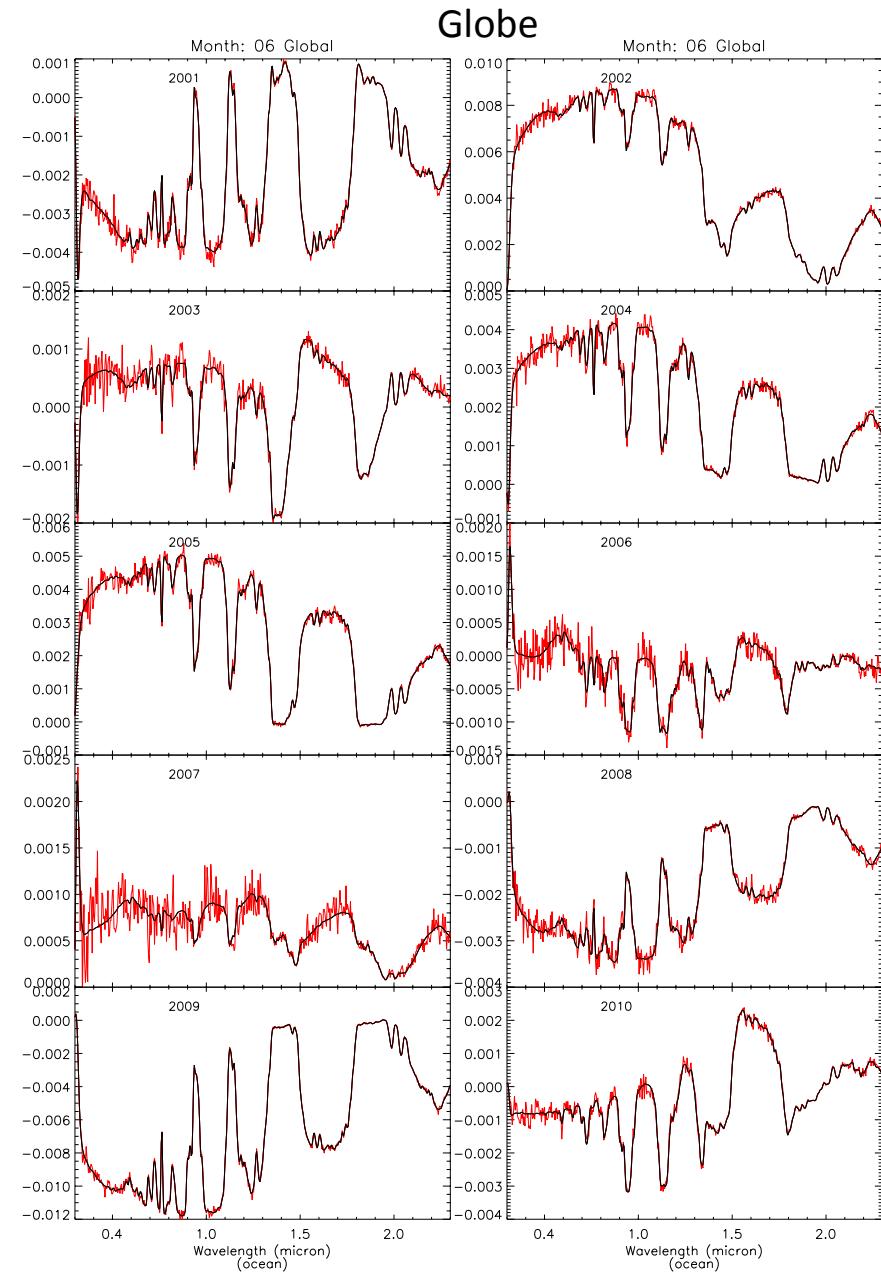
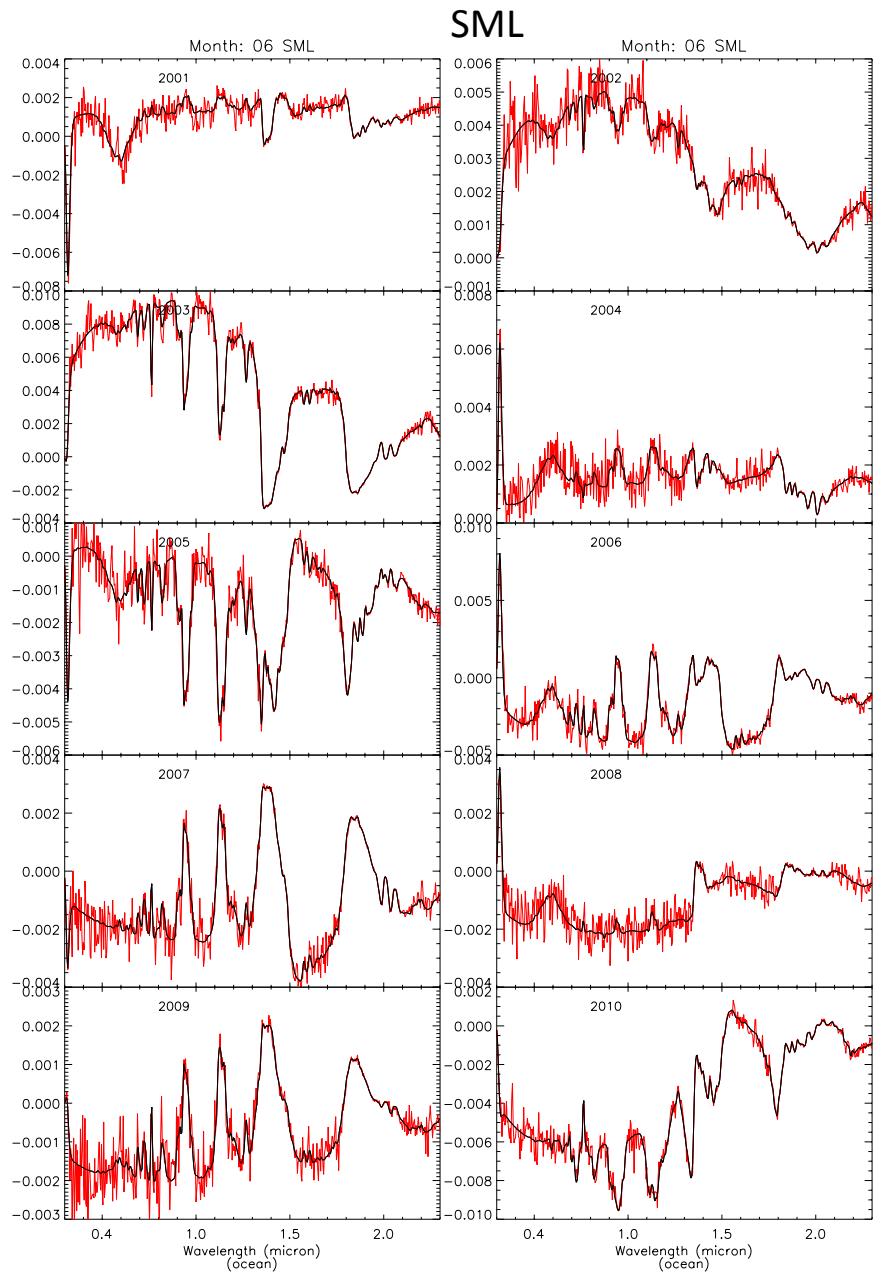
LSE



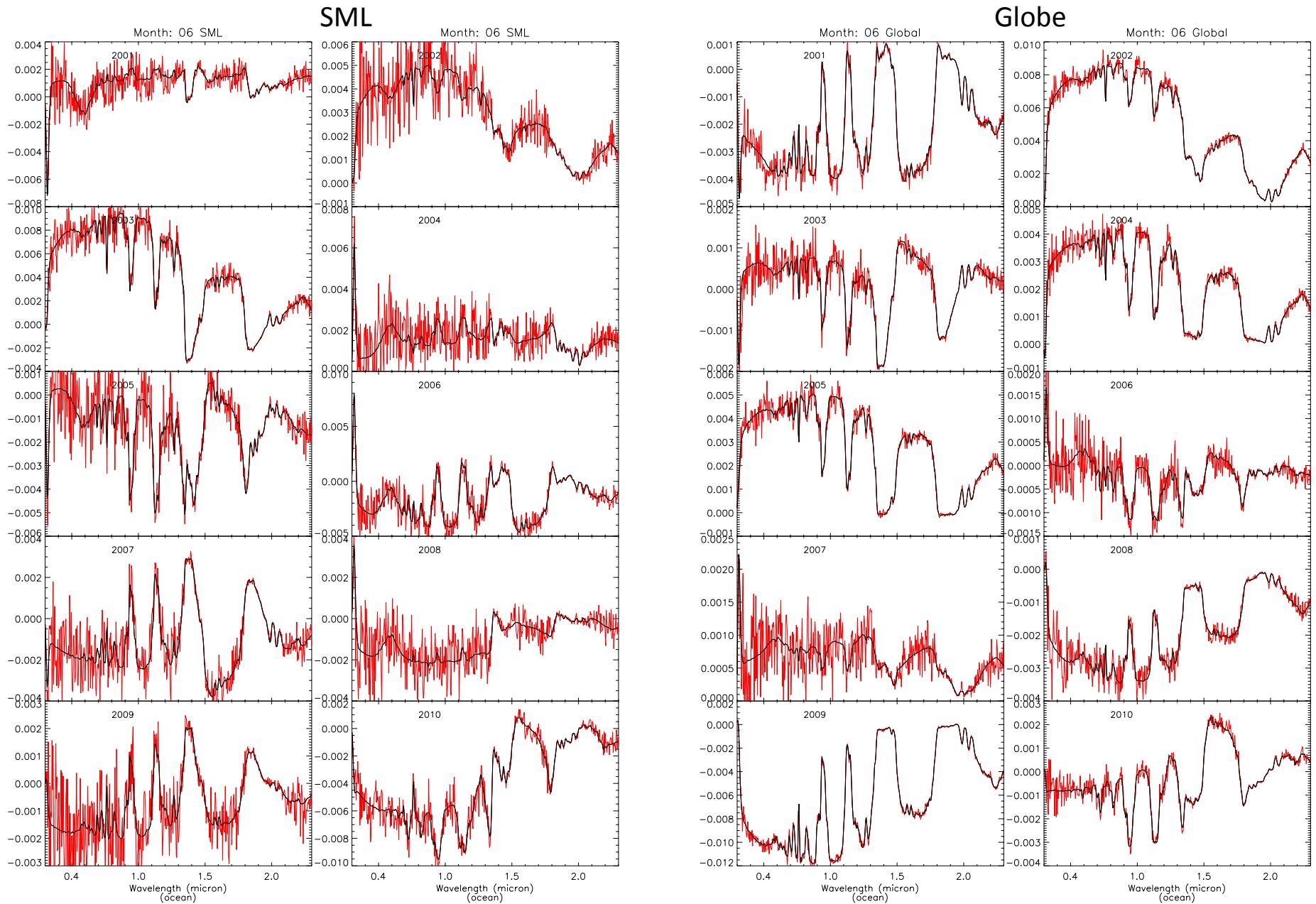
1. Uniform distribution: -0.3% to 0.3%
2. Normal distribution:  $\sigma=0.3\%$
3. Uniform distribution: -1.0% to 1.0%

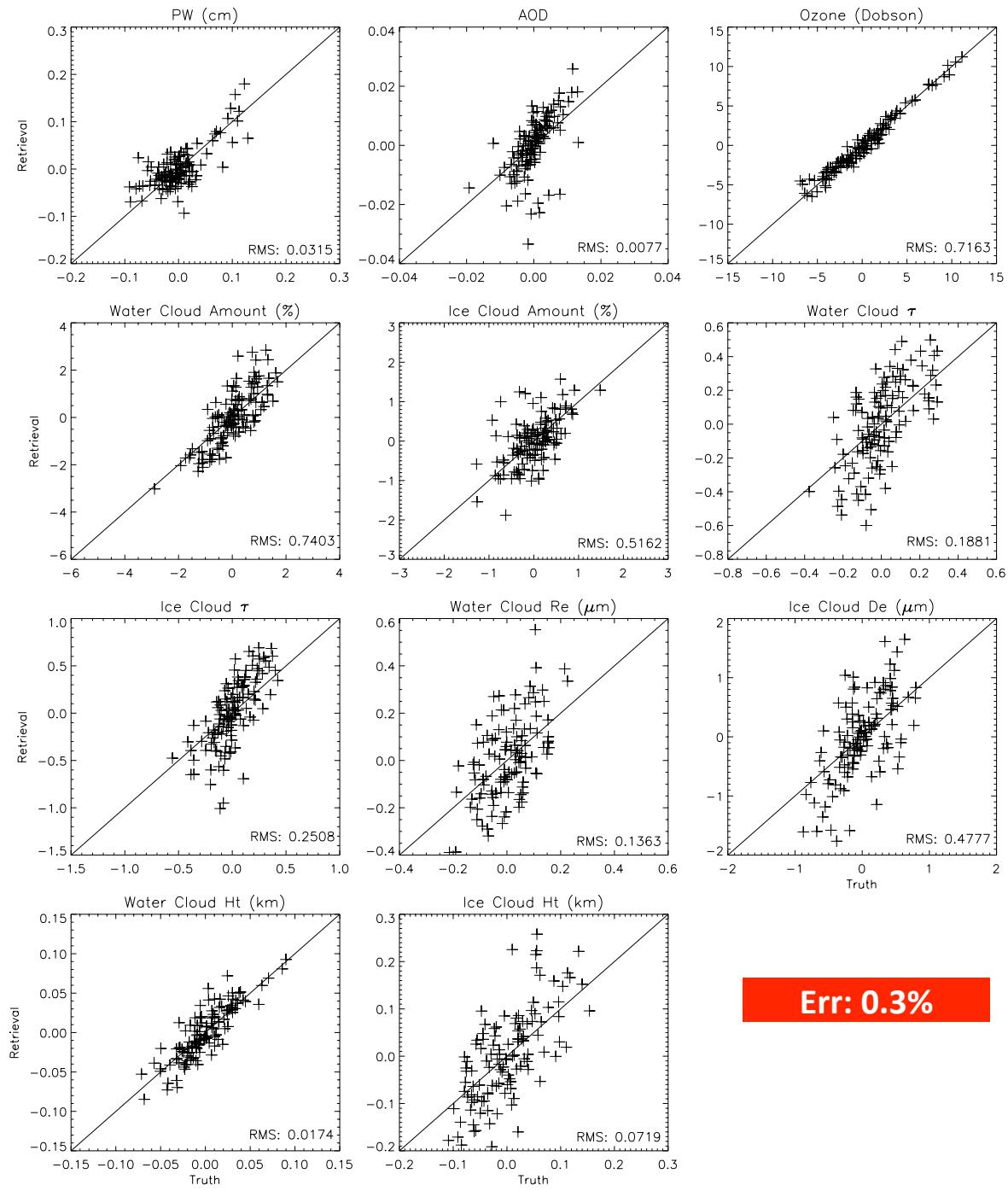


Reflectance anomaly: \_\_\_\_\_ Error-free; \_\_\_\_\_ Error added (0.3%)

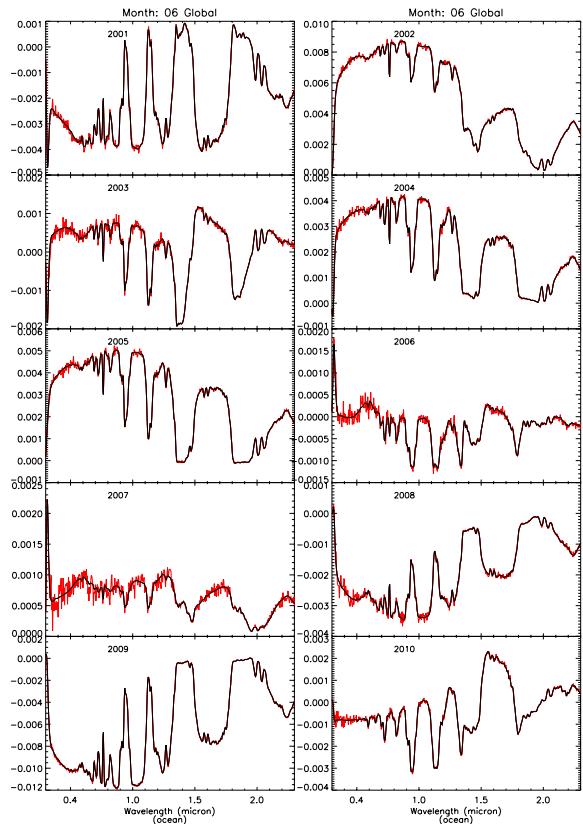


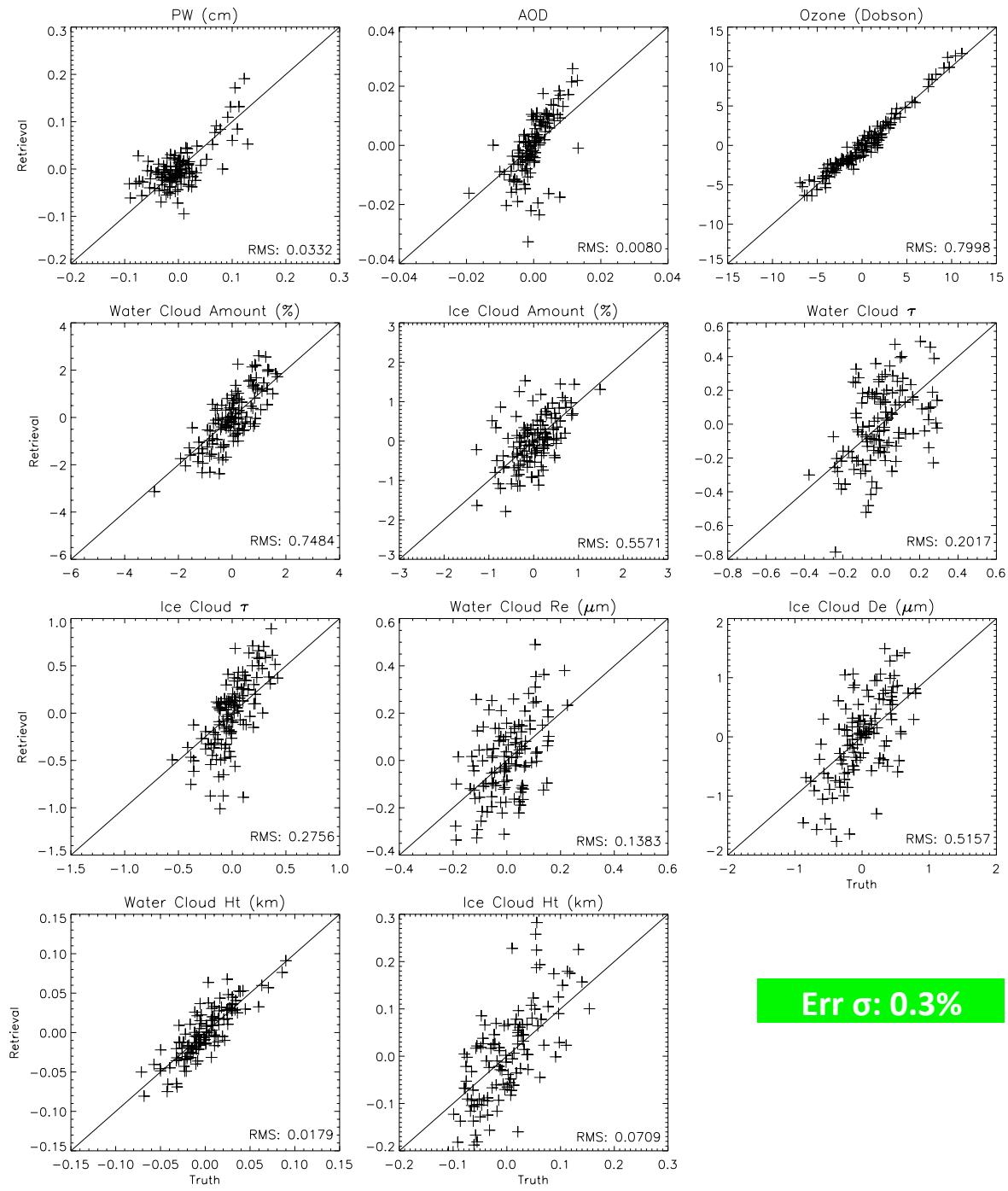
Reflectance anomaly: \_\_\_\_\_ Error-free; \_\_\_\_\_ Error added ( $\sigma=0.3\%$ )



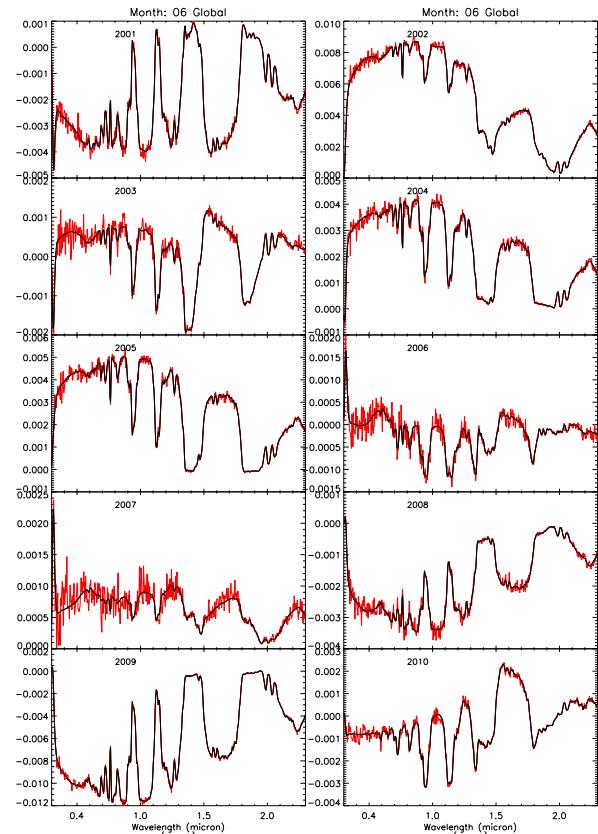


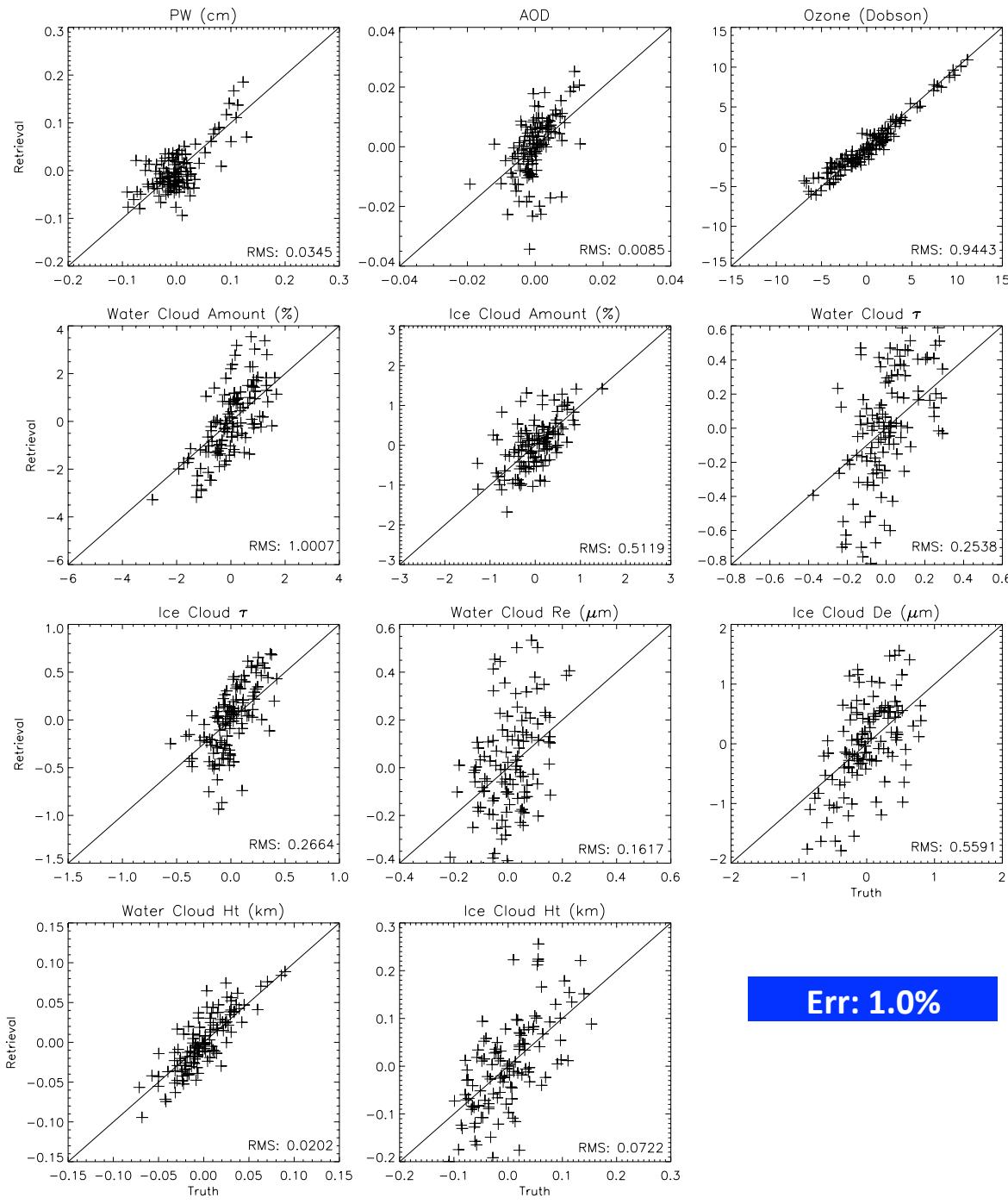
**Err: 0.3%**



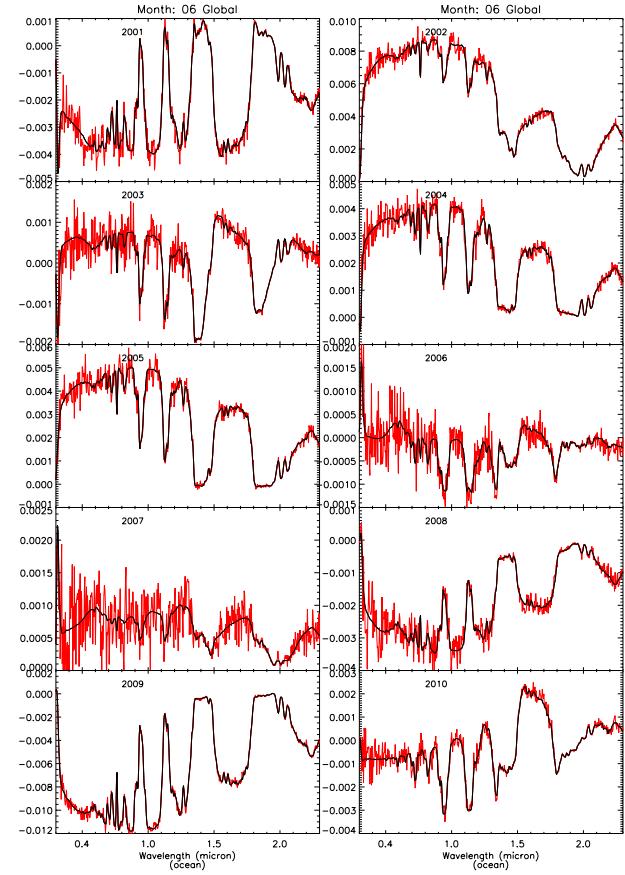


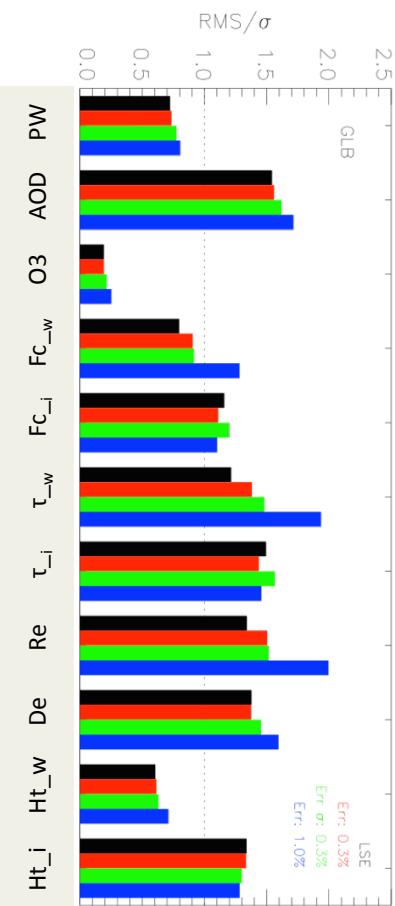
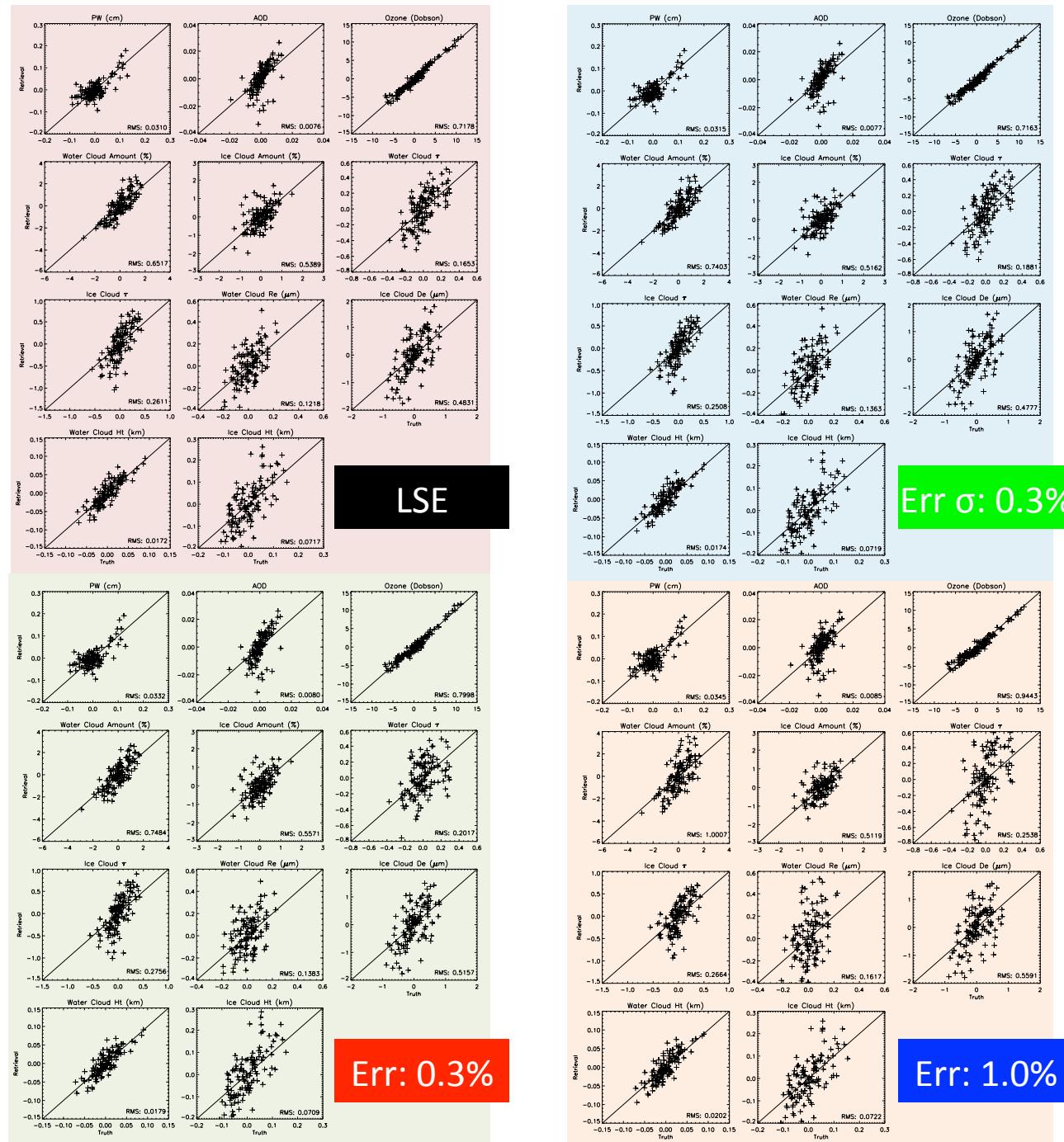
**Err  $\sigma$ : 0.3%**





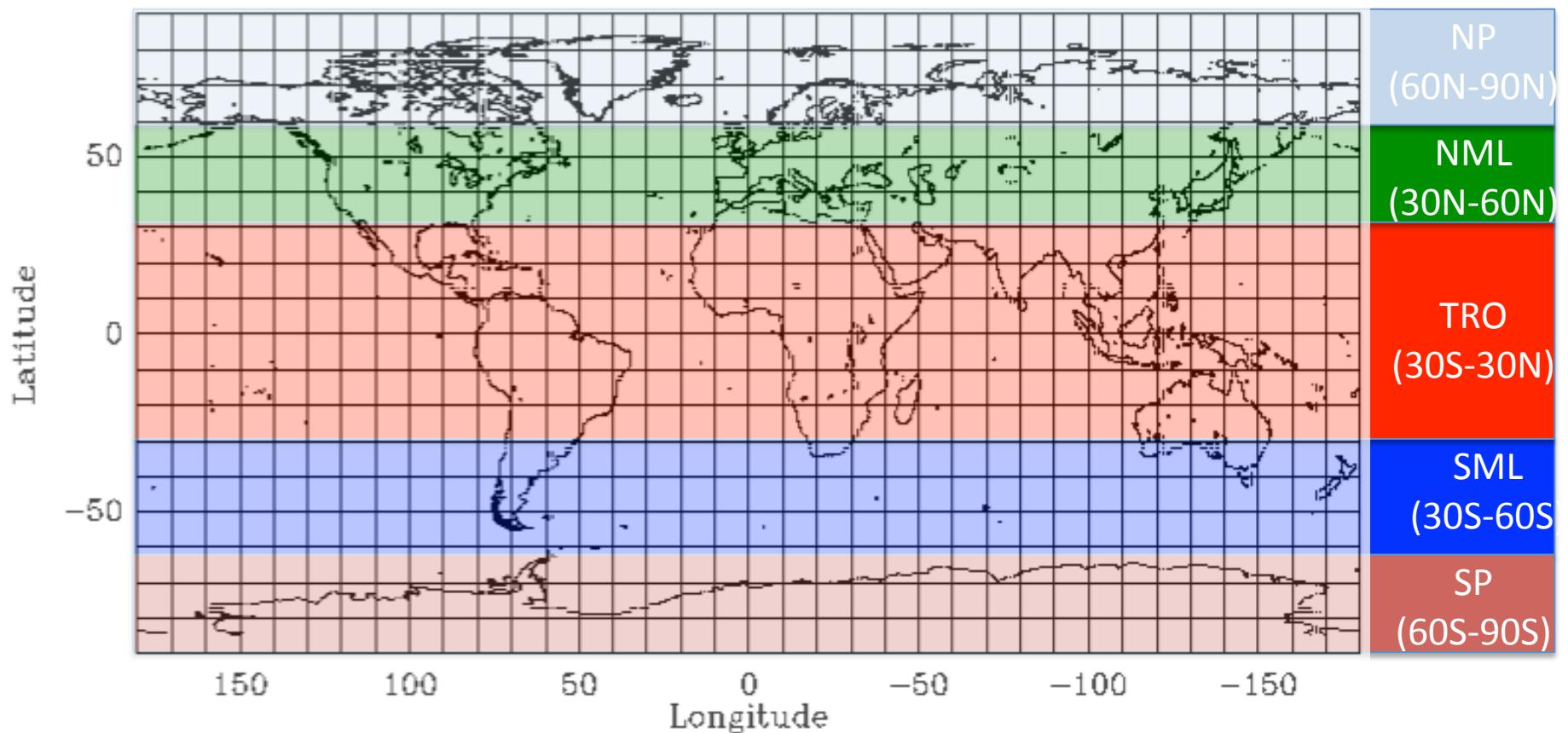
Err: 1.0%

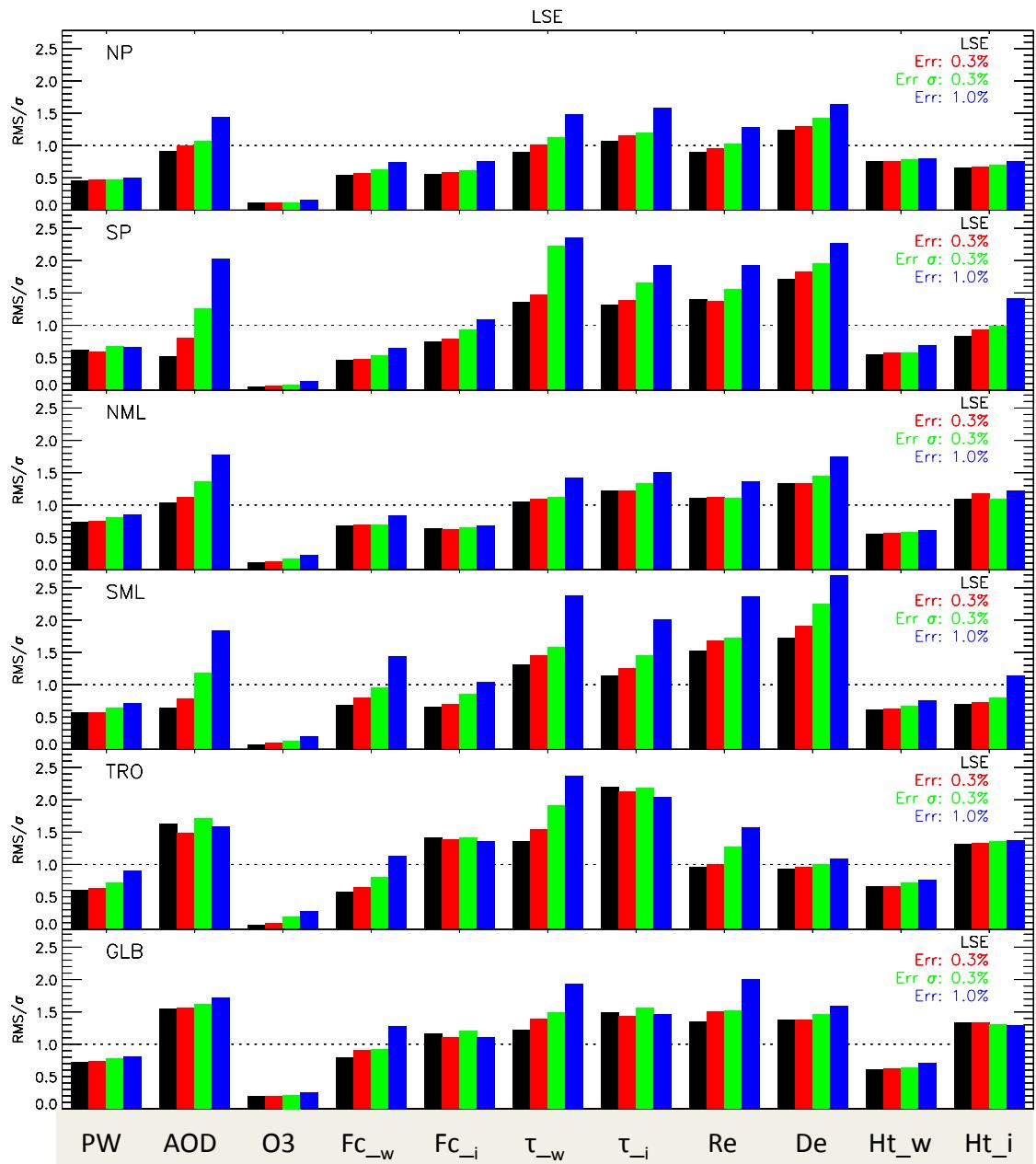




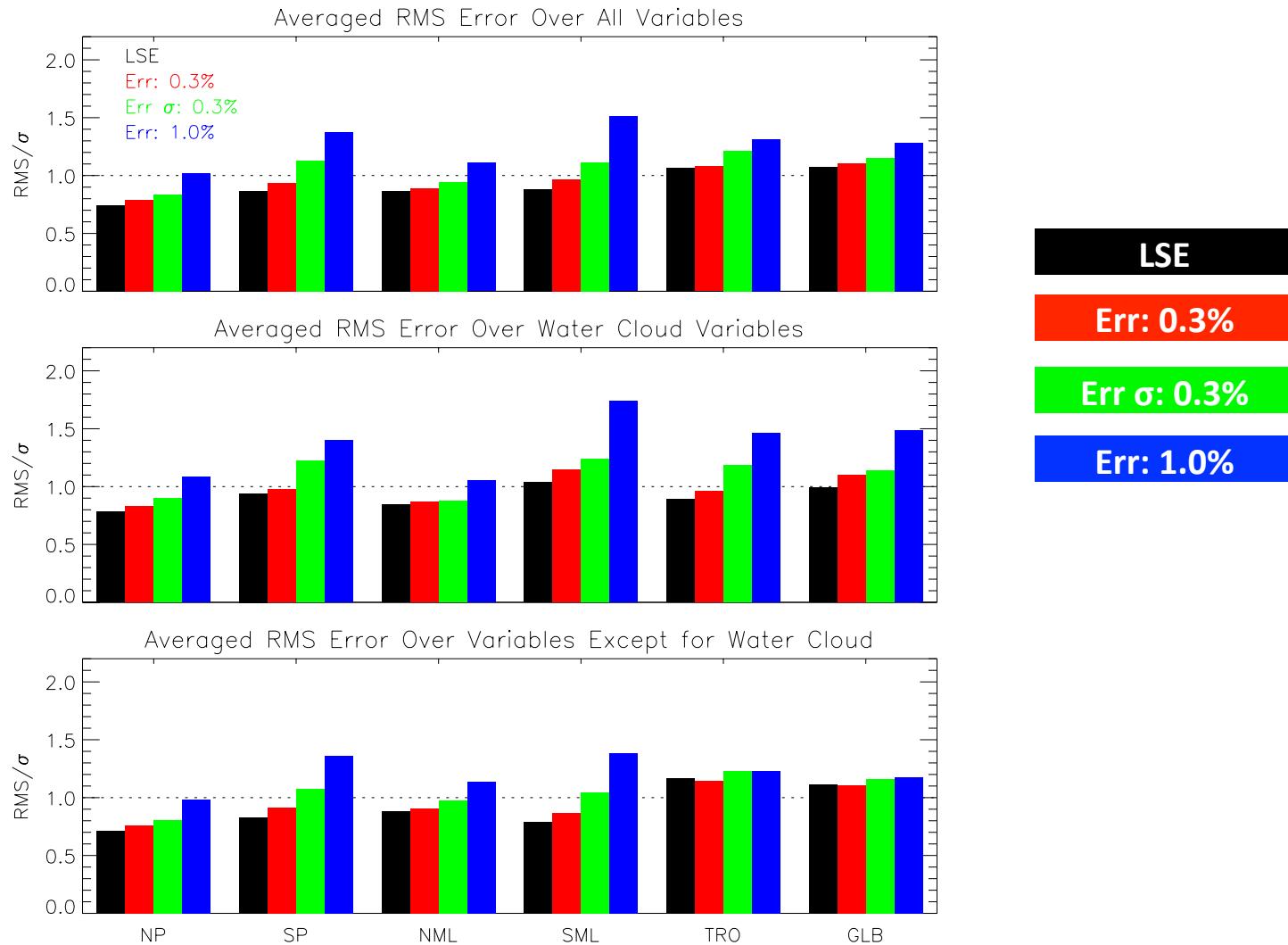
The fingerprints and mean reflectance are also derived for the 5 large latitude regions. The fingerprinting retrieval is tested in these large regions.

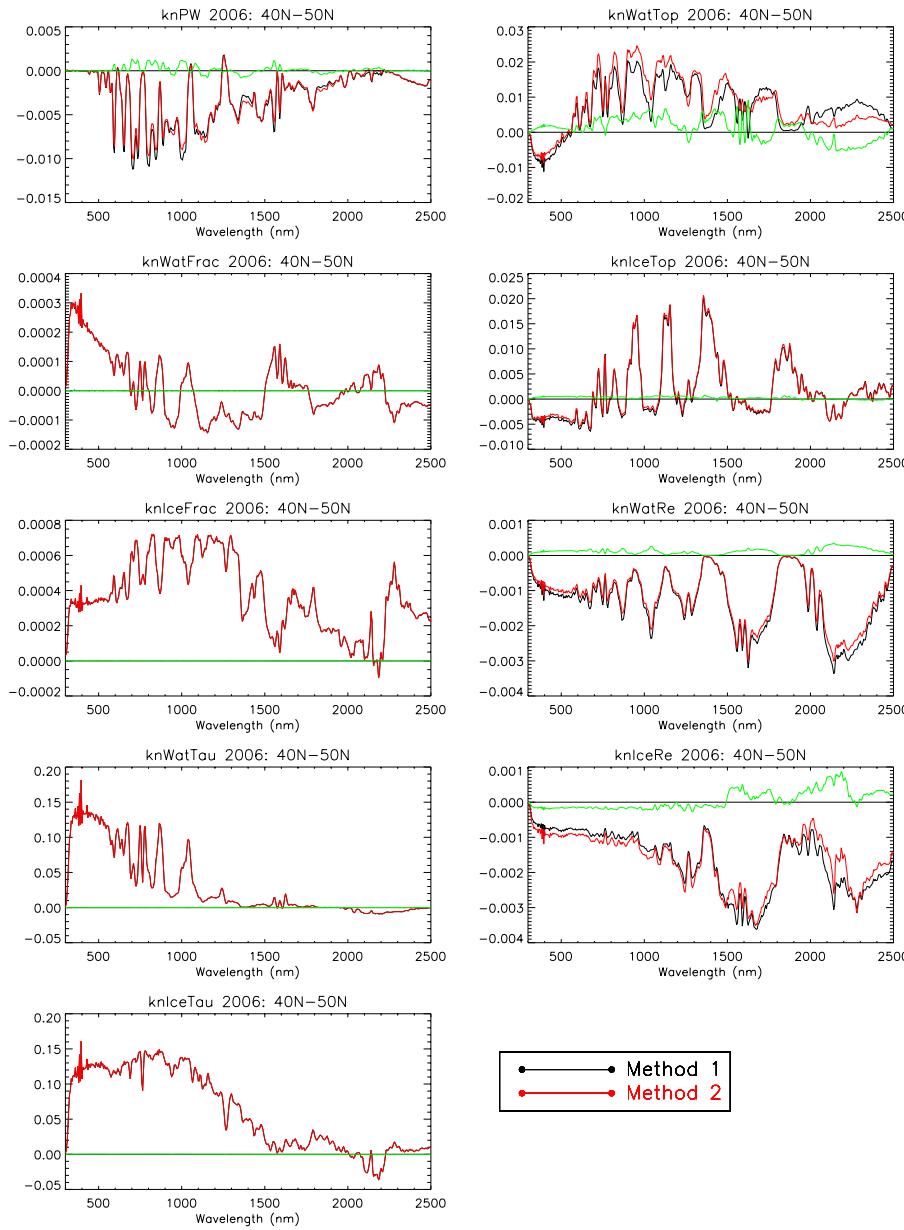
## Five latitude regions

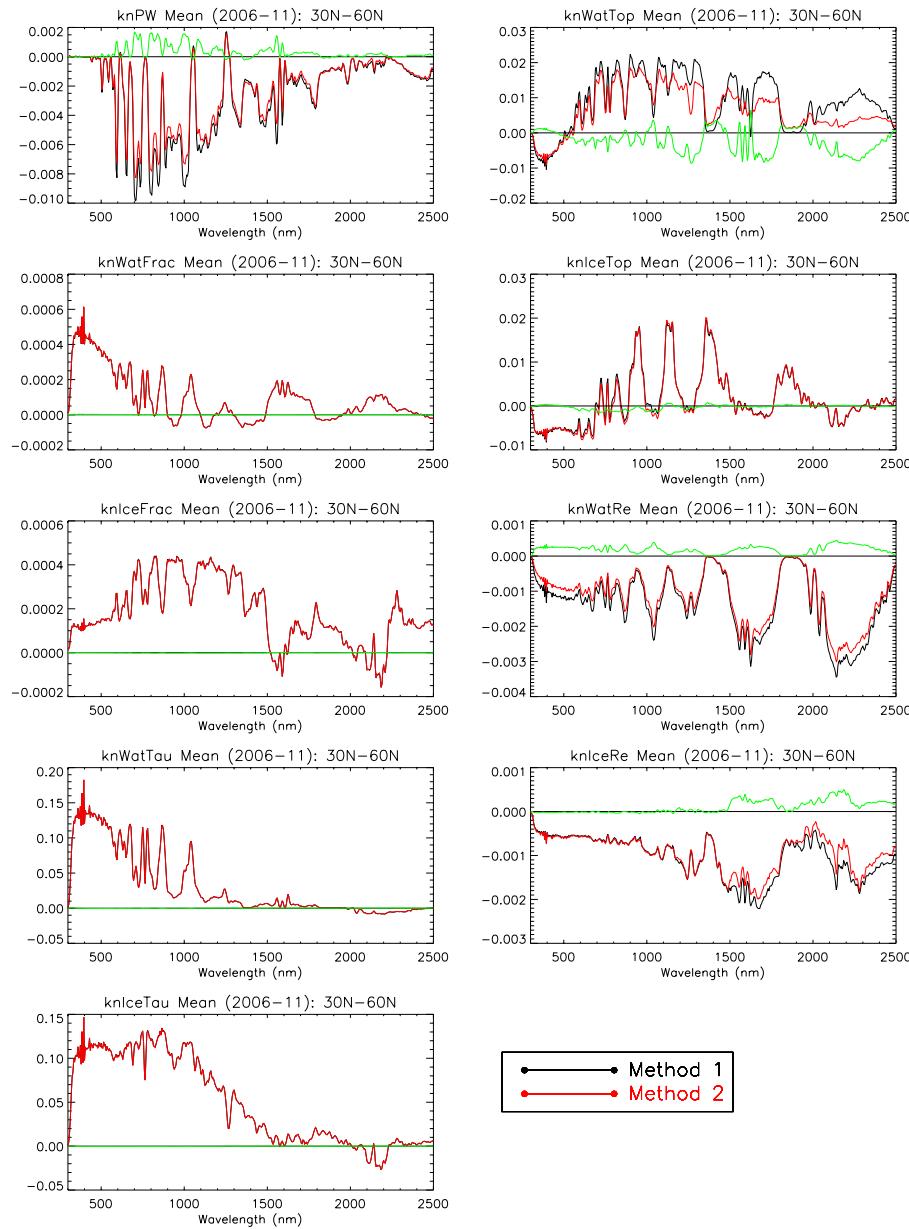




**LSE**  
Err: 0.3%  
Err  $\sigma$ : 0.3%  
Err: 1.0%







● — Method 1
● — Method 2

## Conclusion

- ✓ Ten years of satellite data are used to generate solar spectral fingerprints and monthly mean reflectance spectra to test the concept of spectral climate change fingerprinting using the RS spectrum.
- ✓ The effect of three types of random error in data on fingerprinting retrieval is tested. It is found that fingerprinting retrieval accuracy is not sensitive to the random error.
- ✓ Fingerprinting retrieval of water cloud variables appears to be more sensitive to the random error than other variables.
- ✓ The regional mean spectral fingerprints obtained from the two different methods show good agreement. The largest difference is shown in the fingerprints for water cloud height.